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Perspectives in Observational Cosmology

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1. INTRODUCTION

Cosmology is a reflection on the nature and structure of the universe as a whole and single entity. Although this ambition as a quest of the human mind is easy to express in a few words, its translation into scientific terms has been a long and painful historical process.

Astronomical observations have led, on one hand, to a continuous improvement in understanding individual objects, such as the sun, stars, and galaxies, and on the other to the foundations of physical cosmology, i.e., to a set of partial answers to the initial question asked about the universe.

Observations of cosmological importance may be traced early: Galileo assessing the "changing" nature of solar surface material, which today underscores a fundamental cosmological principle: physical laws are the same for any observer in the universe. The Copernican point of view, refusing to the earth a privileged point of view, is also a methodological principle of cosmology, but it was only validated by Tycho Brahe's accurate observations of Mars. Observing the fact that the sky is not uniformly bright (Olbers' paradox, 1748–1840) led to the early conclusion that a uniform, static, homogeneous space was not acceptable.

Modern cosmology is based on a few observational facts, namely the expansion of the universe, the blackbody background radiation, and the helium abundance. The recession velocity was discovered by Hubble, thanks to the combination of a new telescope of unsurpassed collecting efficiency (more than ten times the previous ones) and an efficient detector, the photographic plate, allowing long time integration. The discovery of background radiation (Penzias and Wilson, 1962), was not searched for intentionally, but was discovered with a radioantenna of exceptional sensitivity: this new evidence met the prediction of Gamow's model (1940) and earlier

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unexplained observations of a molecular rotational temperature of 2.7 K (McKellar, 1940) in interstellar space. The third major observational fact—the helium abundance—is not the result of a single measurement, but an intricate conclusion of a large body of observation, both of stars and the interstellar medium, interpreted in a complex frame of models of stellar nuclear evolution and radiative transfer. It is clear that the modern concept of an evolving universe could not exist without a broad diversity of observations, involving star formation, chemical evolution of galaxies, galaxy formation, etc.

These remarks demonstrate how observations, based on instrumental progress, have been essential to cosmology. In Section 2, I present the areas of progress and in Section 3 the related instruments expected in the coming years. In Section 4, I identify a few key areas where one suspects that observation will bring results of cosmological importance.

One nevertheless should not forget the lessons of the past, i.e., the sometimes unexpected character of cosmological discoveries.

2. OBSERVATIONAL PERFORMANCES

Access to space-based instrumentation has reduced the severe limitation on observing the electromagnetic spectrum, which is today accessible from γ-rays to radio waves. Improving the sensitivity of detection and the angular resolution of images remains a constant goal. Moreover, new carriers of information—neutrino and gravity waves—are of a great potential value for cosmology and may emerge as a new branch of observational astronomy.

2.1. The Detection of Electromagnetic Radiation

Every spectral domain carries the signature of specific physical phenomena: thermal radiation, discrete transitions in nuclei, atoms, molecules, molecular aggregates, solid grains, etc. At each wavelength, the sensitivity of a telescope, hence its ability to detect remote objects of cosmological importance, is set by its collecting area and its detection system.

The longer the wavelengths, the easier the construction of large collecting areas, since the required accuracy of the mirror surface is relaxed. Equivalent telescope diameters stage from a fraction of a meter (γ-rays) to hundreds of meters (metric radio waves).

An ideal receiver should produce a measurable signal for a single photon. The human eye is close to this, since it detects, with quantum efficiency ~ 0.8, about one quantum per second, unfortunately with a limited time integration capability.

Astronomical receivers approach this performance from γ-rays to near infrared and are slowly but continuously being improved at longer wavelengths. Then it is the quantum nature of light which imposes its limitation. For N received photons, the residual $N^{1/2}$ fluctuation limits the accuracy to $N^{-1/2}$, improved with long-time exposure and large collecting areas.

Two perturbing factors intervene above this fundamental limit. In the infrared, signal photons are diluted in the local thermal emission of instruments and atmosphere, which produce N' photons, with $N' \gg N$. The fluctuation $\sqrt{N'}$ dominates and degrades the accuracy, leading to a signal-to-noise $N/\sqrt{N'}$. Cooling the instruments improves the situation, and the first complete sky survey in the infrared (1983) (10–100 μm) was obtained with a cooled telescope ($T = 4$ K; 60 cm diameter).

Moreover, remote objects are always observed through a luminous veil due to the earth's immediate surrounding: luminescence and thermal emission of the earth's atmosphere, scattering of solar radiation by the thermal emission from the interplanetary dust particles (zodiacal light), stellar background of the galaxy. This ubiquitous veil, likely to be nonuniform at a scale of a few arc seconds, makes it difficult to discriminate faint remote sources of similar scale and might represent an ultimate limit to our deep sounding capability. A cosmological window around 3.5 μm exists, between the zodiacal scattered light and the thermal emission. At radiowavelengths larger than 50 cm, the diffuse galactic emission is so large that remote objects can only be perceived if they are small ($\leq 1''$) and therefore appear with sufficient contrast.

The condition for the progress of cosmological observation rests clearly on a few factors: increase of telescope diameter, progress of infrared and radio receivers, long exposure, space observation, and exploitation of cosmological windows.

2.2. Imaging Electromagnetic Radiation

Making spectra and images are the two main goals of astronomical observation. The first one is met with sensitive detectors, the second is more demanding. Angular resolution has been critical to cosmological progress, from Tycho Brahe's measurements to the determination of quasar location in space based on their angular size (Allen *et al.*, 1960). The maximum angular resolution of an instrument is given by the ratio of the wavelength to its physical extension (baseline). The largest angular resolution achieved today (~80 μarcsec) is paradoxically reached at radiowavelengths (millimetric), with instruments extending over intercontinental baselines.

A similar resolution would be available at visible or IR wavelengths on a baseline of a few hundred meters, but atmospheric fluctuations have long limited the resolving power of optical telescopes to ~1 arcsec. Recent and rapid developments circumvent this limitation, reaching 1 marcsec at optical wavelength. The remarkable properties of the photographic plate, which has been available for over a century, may hide a difficulty to which observation is confronted: the need for a receiver with a great number of pixels. A photographic plate may easily contain 10^9 pixels, but other modern photoelectric image detectors are more modest: 10 pixels in γ, 10^2-10^3 in X, 10^6-10^7 in UV and visible, 10^3-10^4 in infrared, 1-10 in radio. With modern technologies in microelectronics and solid state physics, considerable progress is expected, of paramount importance for deep sky mapping: a complete image of the celestial sphere at 1 arcsec resolution—the typical size of the remotest known galaxies—requires 5×10^{11} pixels.

2.3. New Information Carriers

Photons are not exclusive carriers of information. Any wave or particle for which the universe is reasonably transparent, and which can be detected by a suitable interaction, is fit to be an information carrier. Meteorites of local solar system origin contribute more to cosmogony than to cosmology. Cosmic rays are atoms covering the whole mass spectrum of chemical elements, but are mostly of galactic origin, again local.

Two new messengers may bring radically new contributions in the future. Gravity waves are generated by any local change in mass distribution affecting the quadrupole moment of the distribution; they carry energy which is difficult to detect, since the gravitational interaction is about 10^{37} times weaker than the electromagnetic one. The intensity of a gravity wave may be measured by the variation δh of a cylindrical mass of length h. Existing receivers reach $\delta h/h \sim 10^{-18}$, while 10^{-19} to 10^{-22} are needed to detect nearby and likely events such as star collapse during a supernova event. Indirect but convincing proof of gravity waves comes from the observed energy loss of a binary system, the pulsar PSR 1913+16 (Taylor and Weisberg, 1982), exactly consistent with the predicted gravitational radiation carried away.

Neutrinos, neutral and stable, travel easily in a transparent universe, and keep the information from their source, even at long distances. Several "neutrino telescopes" are under study, using, for example, the transformation they induce of Ge atoms into unstable Ga atoms. Detecting neutrinos encounters the same basic limitation as detecting photons, except for an increased difficulty due to the extremely small value of interaction cross sections. The first observation of astronomical neutrinos from outside the solar system was made in 1987, where 13 events accompanied the optical detection of the supernova 1987a in the Large Magellanic Cloud.

3. THE INSTRUMENTS OF TOMORROW

Four main parameters characterize an observation: the wavelength range, setting the appropriate technology; the sensitivity, which sets the weakest observable objects at the required spectral resolution; the ability to make images at a given number of pixels; and the angular resolution. Future instruments aim to improve any or all of these, each having its impact on observational cosmology.

3.1. Observing from the Earth

New large optical telescopes for the visible and infrared (up to 25 μm) are under construction: the *Keck* telescope (10 m) in Hawaii, the European *Very Large Telescope* (16 m equivalent) in Chile, and a flourishing of 8-m telescopes in both hemispheres. These instruments, based on light primary mirrors of novel technology, will increase the sensitivity in spectroscopy, since the atomospheric veil limitations are less severe in narrow spectral bands.

New fiber optics techniques will give simultaneous spectra of a large number of galaxies within a field of view. Objects such as quasars smaller than the limit imposed by the earth's atmospheric turbulence ($\sim 1''$) are better extracted from the veil background when the images are corrected for the turbulence: new techniques of adaptive optics may lead to routine imaging at 0.1 arcsec resolution or better and a great gain in contrast for deep sounding of the universe.

3.2. Space Observations

The goal is to place telescopes in space, possibly smaller, but free of atmospheric absorption or emission. Ultraviolet spectroscopy and deep imaging are the goals of the *Space Telescope* (launch plan 1990).

Infrared and submillimeter ranges are the aim of three great programs, all using modest-size (<1 m) telescopes, but cooled at a temperature of ~ 4 K to avoid all instrumental background. Ultimate sensitivity limitation to remote signals will likely come from the thermal emission of the local interplanetary and interstellar medium. The *Cosmic Background Explorer* (launch 1989) studies at various angular scales the thermal 2.7 K background radiation. The *Infrared Space Observatory* (launch 1993), and its likely successor the *Space Infrared Telescope Facility* (launch <2000?), are devoted to imagery and spectroscopy of remote objects.

At high energies (X and γ), a sensitivity gain of two orders of magnitude is expected, compared to the first generation of instruments. These gains mostly result from an increase in collecting area.

Imaging capability is also in progress: from the degree to the minute of arc in γ, toward a tenth of an arcsecond in X, comparable to the values quoted above at visible and UV wavelengths. Space missions include X-ray observatories such as *XMM* (Europe) or *AXAF* (NASA) and γ-ray observatories.

3.3. Interferometric Imaging

High-angular-resolution imaging deserves special attention. Networks of radiotelescopes, such as the *Very Large Array*, already reach 0.1 arcsec: the structure of gas motion in and between remote galaxies ($z \leq 0.1$) is observable. Long-baseline intercontinental interferometry (*VLBI*) reaches milliarcsec at centimetric and less than 100 microarcsec at millimetric wavelengths. The limits imposed by the size of the earth will be suppressed by placing new antennas in orbit (*QUASAT* project), able to reach nanoarcsec resolution. Quasars or compact galactic nuclei will be resolved even at $z \geq 1$.

A similar approach is now extended to optical wavelengths, with modest-size telescopes (≤ 1 m) on baselines of a few hundred meters, but resolution is already comparable to the one obtained with radio intercontinental interferometry. A new generation of optical interferometers is in preparation, combining large mirrors, like the *Very Large Telescope* (8-m mirrors) and leading to a considerable sensitivity gain. The third generation of interferometers, to be placed in space or preferably on the moon, will neither be limited in spectral range nor in baseline extension. Considerable sensitivity is foreseen, with objects of magnitude 21 ($z \sim 0.1$) resolved in less than 1 hr of observing time.

These programs show that the photon contribution is not yet vanishing, but other, less conventional programs may also bring contributions to cosmology, such as the observation of a neutrino background radiation at a predicted temperature of 3 K, or of magnetic monopoles.

4. KEY COSMOLOGICAL OBSERVATIONS

Although one should not exclude that new observations may radically modify our current cosmological models, it is likely that the Friedmann-Lemaitre model will remain the accepted frame in which the value of a new observation is discussed. The redshift z is the adequate parameter to order these in epochs of increasing distance and age. Some cosmological data relevant to $0 \leq z \leq 0.1$ are quite well established, but require improvements. The data for $0.1 \leq z \leq 3$, up to the remote quasars, require serious progress. Finally, the most critical ones deal with the epoch following helium synthesis. Inferences on a more remote past seem to result more from theory and experiments on particles than on direct observational constraints. I order what follows in three areas: the global structure of the universe, the value of the main physical constraints, and the evolution of the young universe, and discuss the impact of observations on these three points.

4.1. Global Structure of the Universe

Is baryonic matter filling the universe uniformly at $z \sim 1$ scale? Are the 10^{11} known galaxies forming a fluid close to a perfect gas? What is the repartition of matter at $0 \leq z \leq 5$? and beyond?

All the answers rest on three-dimensional localization of galaxies, which itself rests on an accurate determination of expansion redshifts after correcting for local motions, assuming a constant value of the Hubble parameter H_0, and neglecting evolutionary effects of galaxies at distances less than 100 Mpc. The *VLT* and the *Space Telescope* should give unbiased galaxy samples, with accurate ($\leq 75\ \mathrm{km}^{-1}$) velocity determination, down to magnitude 15 in the blue. For giant elliptical galaxies, the redshift-magnitude relation will be extended to $z = 1$, as well as the relation between magnitude and galaxy count (filling factor). The relation of galaxy count to z will be extended with 10% z accuracy, from its present limit ($z = 0.3$) to $z \sim 1$ for most of the rich clusters of galaxies ($m_v \sim 23$–25). This data set will provide a precise view on the organization of galaxies in clusters, the repartition of voids in these, the existence of a filamentary or sheetlike structure, likely related to the galaxy formation process.

Deep sounding ($z > 4$) requires powerful sources, such as quasars or radiogalaxies. The sensitivity of X-ray observatories should allow quasar observations until $z \sim 10$ and give their spatial distribution: the organization of quasars in clusters is a controversial question, because of the limited and biased available sample.

The knowledge of the background radiation, the modern version of the Olbers' problem, is a critical point for understanding the universe for $5 \leq z \leq 10^9$. The measurement of the spectrum is difficult and the current confidence interval sets a blackbody temperature $T = 2.7 \pm 0.2$ K; spectral distorsions could signal the existence of a pregalactic generation of stars. The $T(z)$ dependence is also a critical test of the matter-radiation decoupling.

The measurement of isotropy is another indication of the uniformity of the universe at the recombination time ($t \sim 10^{13}$ sec, $z \sim 10^3$). The current measurement accuracy is 3×10^{-4} and shows a local motion of the Local Group of galaxies toward the Virgo cluster at a velocity of $550\ \mathrm{km}^{-1}$. No other anisotropy, at an accuracy of 10^{-4}, has yet been firmly detected. These measurements are extraordinarily difficult, but the satellite *Cosmic Background Explorer* should improve the accuracy by a factor 3, at the angular scale of a degree, between 1.5 and 3 cm wavelength. Some anisotropy may be due to the interaction of the radiation after recombination with galaxy clusters (Sunyaev-Zeldovich effect) and lead to a determination of the mass present in the form of intergalactic gas.

Searching for anisotropies of 10^{-5} at smaller angular scales is even more difficult, requiring a large antenna (~ 30 m) in orbit. This measurement is the only one which would determine the fluctuation at a scale of a protogalaxy at $z \sim 100$. Although quite unlikely, the hypothesis of discrete sources at $z \gtrsim 10$ being responsible for the 2.7 K background cannot be fully discarded without this measurement.

Visible and infrared backgrounds are virtually impossible to detect because of the immediate surroundings of the earth and sun. Conversely, it is crucial to establish the origin of the X (3-50 keV) and γ observed backgrounds: is it due to a primordial intergalactic gas ($T \sim 5 \times 10^8$ K), or to the accumulated radiation of a discrete background of quasars, or to a relict of annihilation (at about 0.5 MeV) of baryons and antibaryons, the latter hypothesis being supported by the very thermal character of the observed spectrum? The measurement of the X spectrum between 10 and 100 keV, up to $z = 4$ for the continuum and $z = 2$ for the Fe lines and of the γ spectrum for a large sample of quasars by observatories having a sufficient angular resolution (≤ 1 arcmin), should answer this question and assign a mass and a temperature to the eventual intergalactic gas. To date, this gas has only been detected with certainty by the X emission of FeXVII within galaxy clusters at $z \leq 0.75$. This gas may also interact with the 2.7 K background by inverse Compton (Sunyaev-Zeldovitch) effect.

4.2. The Physical Constants

The models of an expanding universe are constrained by a limited number of measured quantities, among which are the Hubble constant $H(t_0)$, the deceleration parameter $q(t_0)$, and the total mass-energy density $\rho(t_0)$, where t_0 is the present value of the cosmic time. $H(t)$ and $q(t)$ are related to the first and second time derivatives of the expansion. Their measurement provides the first terms of a limited power series around the present cosmic time.

The Hubble constant $H_0 = H(t_0)$ is known within a factor of two, where the uncertainty does not come from noisy data, but from systematic errors. This in turn creates uncertainties of a factor 8 on quantities related to volumes, such as densities. The distance scale will benefit from the *Hipparcos* satellite (1989), recalibrating the basic "stick" represented by the distance of the Hyades stellar cluster. The *Space Telescope* allows the observation of the pulsating stars Cepheides up to the Virgo galaxy cluster (10 Mpc) at a magnitude $m_v = 26$ or 27 and of the globular star clusters in the Coma galaxies cluster (60 Mpc) after careful calibration on the galaxy M31 (1 Mpc).

New methods are proposed for absolute distance measurements, such as the relation of the absolute luminosity of a supernova with the velocity of the gas it ejects, a measurement which can only be carried out with a highly resolving telescope such as the *Space Telescope* or the *Very Large Telescope*. The measurement of the Sunyaev-Zeldovich effect (cf. above) would determine H_0 if carried on a space-borne submillimetric telescope resolving ~1 arc min. The gravitational mirages due to interacting matter on the light path from distant objects to earth, if observed at an angular resolution of 0.1 arc sec at visible or infrared, may also lead to H_0. All these conjugated efforts may lead to H_0 with a 10% accuracy.

The average density of mass-energy $\rho_c(t_0)$ closing the universe is $3H_0^2/8\pi G$ and suffers from the poor determination of H_0, hence varying from 0.5 to 2×10^{-29} g-cm^{-3}. The actual density $\rho_0 = \rho(t_0)$ is estimated by a variety of methods which do not agree. While the baryonic mass derived from its radiation may only be 5% of ρ_c, additional dark matter is indicated by its gravitational effects, and may provide up to 40% of ρ_c at the scale of superclusters of galaxies.

The presence of hidden, nonluminous mass (dark matter), suspected in the solar neighborhood as early as 1932 (Oort, Zwicky), is today confirmed, but at the scale of galaxies, where the luminous matter may represent only 5-10% of the total mass detected by local gravitational effects, with large fluctuation of an order of magnitude or more between galaxies. This determination may be made by measuring systematically the Doppler velocities of peripheral globular clusters in galaxies, tracing the gravitational potential. Their faintness ($m_v = 20$–24) requires large telescopes, such as the *VLT*, to measure the velocity. Other objects are candidates for dark matter: intergalactic gas does not appear to be dense enough; collapsed stars, with too small a luminosity for detection, could exist. Massive star relicts are excluded since their early formation would have produced an excess of heavy elements, which is not observed. Low-mass stars (<0.1 solar mass) or heavy planets are possible, but the coronal X-ray activity of the former should make them detectable in the Local Group of galaxies by planned X-ray observations.

Other nonbaryonic exotic candidates for dark matter have been proposed, but no clear observational tests for their existence have been devised.

Direct determination of the deceleration parameter $q(t_0) = q_0$ is difficult. Its measure directly relates to the density, since the relation $q_0 = \frac{1}{2}\rho(t_0)/\rho_c(t_0)$ only holds in a universe with the cosmological constant $\Lambda = 0$. The difficulty of measuring q_0 is due to the fact that the empirical observed relation between redshift z and distance is only sensitive to q_0 at $z \geq 1$, where evolutionary effects of galaxies are not negligible. Correcting for them will require numerous observations at large $z > 1$ to fully understand the evolution of galaxies.

4.3. The Young Universe

Observing the electromagnetic radiation is limited to the recombination epoch ($z \sim 10^3$), while the observation of the helium abundance is an indirect approach to the condition prevailing at $z \sim 10^9$. The discovery of absorption lines in quasar spectra (Boksenberg, 1977) reveals the existence of intergalactic gas which may be in primordial clouds or associated with galaxies. Ionized helium has not been observed, since its resonance line, redshifted at $z \gtrsim 3$, will only be observable with the *Space Telescope* and give a direct evaluation of its ionization. Neutral helium at smaller z requires a spaceborne UV telescope observing at shorter wavelengths, with a spectral resolution of $\sim 10^4$ to separate D and He lines.

Such measurements may settle the question of primordial abundances. The problem of the formation of galaxies ($z = 30$–100) is extremely difficult to attack with *ab initio* models, since a reasonable set of initial physical conditions is not available. The measurements of fluctuations in the background thermal radiation, already mentioned, may bring some indications. Moreover, the intense visible and ultraviolet radiation of these protogalaxies would be shifted to the infrared today, but extremely difficult to discriminate from the zodiacal and galactic background emission. It will be searched for by the space observatories *ISO* and *SIRTF*. During the same period, shocks from supernova explosions may have excited the galactic gas at 100 keV, today shifted to 1 keV and detectable by the coming X-ray observatories.

The genesis of quasars is another field of investigation for the *Space Telescope*, which may confirm the systematic association of a quasar with an underlying galaxy. The suspected depletion of quasars beyond $z = 3.5$ could be investigated with the X emission of Fe, for which the intergalactic primordial dust, if any, would be transparent.

5. CONCLUSION

Observations bringing new cosmological insights are technically difficult, but the new generation of ground- or space-based instruments, with a great diversity of wavelength range, unsurpassed sensitivity, and angular resolution, will likely bring a wealth of new results, some of them improving the accuracy of fundamental quantities such as the Hubble constant or the mean density of the universe, others leading to a more detailed understanding on the organization of baryonic matter. Cosmological models for epochs much larger than the Planck time will be more constrained by these new data.

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